A case study of metamorphic housing: the on-demand room

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A case study of metamorphic housing: the *on-demand room*

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Abstract: Metamorphic housing is a vision of homes that perform dynamic adaptations of their physical structures, so as to assist their occupants' activities and life cycle.

This paper presents the *on-demand room*. It is a case study of metamorphic housing, where apartments of a building can be dynamically enlarged when the need arises. The additional space is to all intents and purposes an *extension* of the apartment, as devices and networks are interconnected and customized.

We present the on-demand room and a model of computation formalizing its behavior and then illustrate the research problems that have to be solved to make it a reality. Finally, we describe our plans to demonstrate the on-demand room in an immersive virtual reality platform.

Key-words: Metamorphic housing, sustainable city, resource efficiency, smart home

Résumé : *L'habitat métamorphique incarne la vision d'un lieu de vie qui réalise des adaptations autonomes de ses structures physiques, afin d'assister l'activité et de suivre le cycle de vie de ses occupants.*

Ce rapport de recherche présente une étude de cas d'habitat métamorphique, la pièce à la demande*, où les appartements d'un immeuble peuvent s'agrandir dynamiquement lorsque le besoin se présente. L'espace supplémentaire devient une nouvelle pièce de l'appartement à part entière, car les appareils et les réseaux sont interconnectés et personnalisés.*

Nous décrivons la solution et présentons un modèle informatique qui formalise son fonctionnement, pour ensuite illustrer les problèmes de recherche à résoudre pour rendre la pièce à la demande une réalité. Enfin, nous décrivons le processus qui mènera à la réalisation, au sein d'une plateforme de réalité virtuelle immersive, d'un démonstrateur de pièce à la demande.

Mots clés : *Habitat métamorphique, ville durable, économies de ressources, habitat intelligent*

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1 Introduction

As many other countries in the world, France is going through socio-demographic evolutions, like growth of life expectancy and consequent increase in the number of elderly people, urbanization and resource scarcity. Households experience financial restrictions, while housing costs increase with the raise of real estate and energy prices.

Important questions arise concerning the future of housing policies and ways of living. We observe novel initiatives like participative housing and developing behaviors, including house-sharing, teleworking and longer stay of children in parents' homes.

To tackle the challenges raised by these emerging phenomena, future homes will have to be modular, upgradeable, comfortable, sparing of resources. They should be integrated in the urban context and exchange information with other homes, contribute to reducing the distances to be covered daily and respect the characteristics of the territory where they are located.

We proposed the vision of *metamorphic housing* as contribution to reaching the aforementioned objectives [16]. Enabled by Information and Communication Technologies (ICT) and adaptive building elements, domestic environments will modify their shape and behavior to support activities and changes during the life cycle of occupants, increase comfort and optimize the use of resources. The same physical spaces will be transformed for different uses, giving inhabitants the illusion of living in bigger, more adapted and more comfortable places.

This paper presents a case study of metamorphic housing, addressing the goals of saving space and energy in an apartment building, while preserving residents' comfort: the *on-demand room*, illustrated below.

1.1 Dynamically extending homes: the *on-demand room*

The principle of the on-demand room is that apartments of a building can be dynamically enlarged when the need arises. To this end, a floating space is dynamically conveyed from an apartment to another.

Differently from the process of acquiring an additional all-purpose space, like a meeting room in an office building, the on-demand room becomes to all intents and purposes an *extension* of the apartment. This is obtained by connecting the devices and networks of the on-demand room with those in the apartment, and by customizing the room so that it looks and behaves as if it belonged to the apartment.

The on-demand room can be used as bedroom, teleworking space or any other function. It can also be shared among apartments, to become a place for socialization or co-working.

Depending on the specific deployment, the on-demand room can allow to:

- mutualize built space between residents;
- add flexibility to buildings by enlarging or contracting apartments depending on occupants' characteristics, needs and phases of their life cycle;
- temporarily create private spaces in shared houses or apartments;
- strengthen relations between generations and facilitate in-home care of elderly people, by enabling households to combine the benefits of having a private extra room and a shared space for socializing with neighbors.

Section 2 illustrates in detail the on-demand room, while Section 3 presents the scientific goals to achieve in order to make it a reality. Section 4 describes the rules and means for handling multiple requests of extension, while Section 5 describes the implementation and evaluation strategies. Finally, Section 6 presents related work and Section 7 concludes the paper by illustrating a work plan and some perspectives of generalization of the approach.

2 Description of the case study

This section presents our case study, by illustrating the dynamic transformations and customizations happening when the space is conveyed from an apartment to another (cf. § 2.1) and the proactive actions that are performed to anticipate future occupation (cf. § 2.2).

In order to simplify the presentation, let us visualize the on-demand room concept, by considering a building floor hosting two apartments and a floating space in between them, as illustrated in Fig. 1.

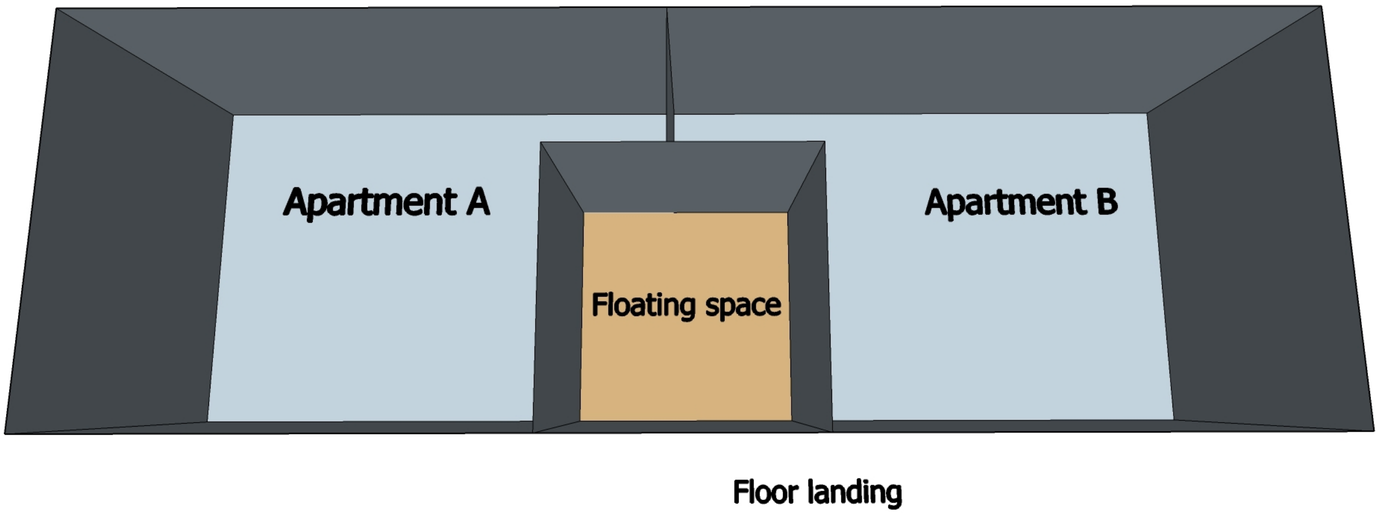

Figure 1: Plan of the building floor

2.1 Dynamic customization of the on-demand room

As we said, the difference between our case study and simply renting an additional room is that the on-demand room becomes an extension of the apartment that requested it. This requires interconnecting the networks and devices of the two spaces and dynamically customizing the room, so that occupants feel like they were in their own dwelling.

Below is a description of the adaptation strategies that dynamically change the on-demand room into an extension of the apartment requesting it.

Physically connecting the spaces When an apartment requests an extension, the floating space is assigned to it. A door appears, allowing occupants to access the space, which thus becomes a new room of the apartment: the on-demand room. This is illustrated in Fig. 2, showing a door connecting the room with apartment A.

Reproducing the owning apartment's ambience To make occupants feel they did not leave their apartment at all, the room adapts its atmosphere so as to resemble the apartment that requested it: lighting conditions, temperature, music and other aspects of the apartment's ambience can be reproduced automatically.

Controlling simple devices When the room is assigned to a particular apartment, devices like light bulbs, electric blinds or HVAC systems require to be controlled from the apartment that owns the room at the moment, via wall-mounted switches, the apartment's domotic control unit or applications running on apartment's mobile devices (smartphones, tablets, etc.). Additionally, the room itself has a domotic control unit that can manage these devices, for instance when customizing the room ambience or when proactively acting by anticipating future requests (cf. § 2.2).

Interconnecting internal networks Wireless and wired data infrastructures (Ethernet, Wi-Fi, ZigBee, telephone, etc.) of the room and of the apartment that temporarily owns the room must be interconnected, so that equipment (e.g., media streaming and playing devices) can communicate with each other. To preserve occupant's privacy, devices in the room should use the owning apartment's Wi-Fi network, so that data are encrypted with that network's private key, not shared with other apartments.

Redirecting context information Sensor data providing information like presence and temperature must be redirected to the right apartment, for applications like HVAC management and security. For instance, if all the occupants of the apartment move to the on-demand room, the domotic unit must know that someone is still home (and not turn the heating off).

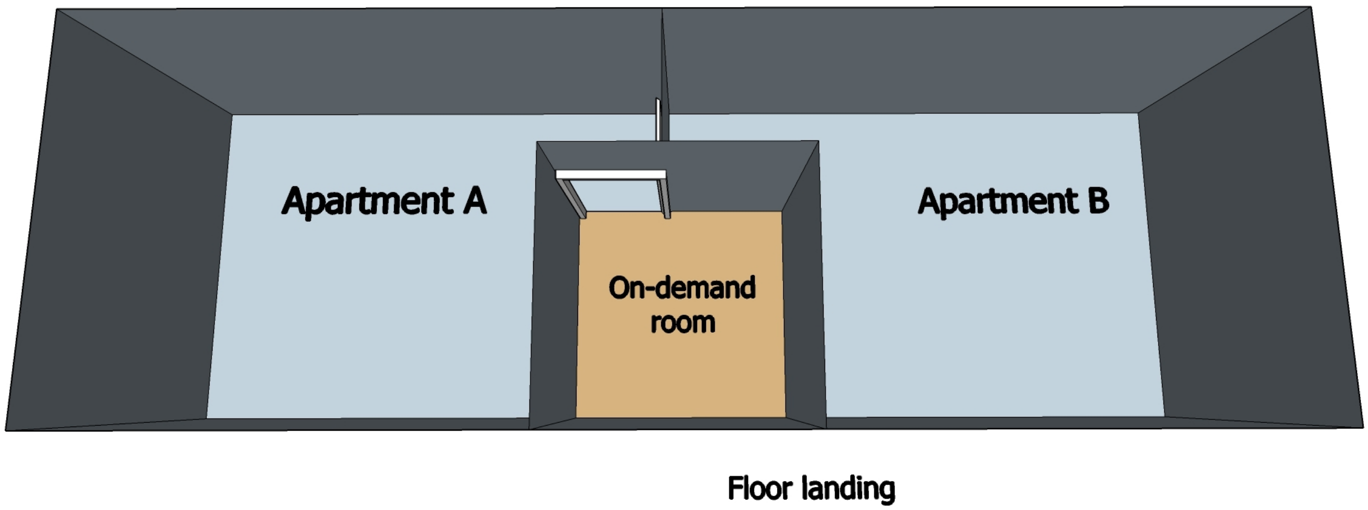

Figure 2: On-demand room assigned to apartment A

Measuring and billing resource consumption Resources are consumed during the occupation, due to heating, ventilation, lighting, electrical appliance use, etc. Consumption must be measured and billed to the right apartment.

Pushing settings to complex devices Devices located in the room, like programmable or learning thermostats, television sets, home theater systems and receivers, digital photo frames, computers, gaming consoles and media players contribute to the comfort and entertainment of occupants and are generally highly customized to user preferences. These devices have to be reprogrammed dynamically with the appropriate settings when the room's owner changes.

Furthermore, these devices sometimes maintain the history of use (e.g., last channel seen on TV, music playlist on a media player). These data have to be stored separately for each apartment, so as to give users the impression of being the only owner of the devices and to avoid disclosing private information.

A simple illustration of some possible aspects of the customization is presented in Fig. 3. The picture shows that the same light bulb is controlled by a switch located in apartment A or B, depending on which one owns the room at that moment. Similar considerations apply to the room's Wi-Fi range extender, presented in the lower part of Fig. 3. The device is dynamically connected to the appropriate router, so as to provide the room's occupants with connection to their apartment's internal network and, through that, to the Internet.

2.2 Proactive behavior of the on-demand room

We now illustrate the proactive functionalities of the room, that is, the actions that it performs to anticipate future events. Proactivity is required to solve room usage conflicts before they happen and for actions whose effects are delayed in time. The underlying assumption is that there exist regularities in the time and duration of occupations, due to user habits. This allows a whole new set of rules for the management of the on-demand room, as illustrated below.

Proactively solving conflicts When allocating the room, regular occupations should have higher priority than impromptu requests, so as to foster appropriation and comfort. If an apartment usually requests the on-demand room for teleworking from 2 to 6 pm every working day, priority will be given to this habit over other requests.

If other occupants ask the room at 1:55 pm, the room will be allocated to them anyway, as there is no certainty that the regular request will actually be issued today and at the usual time. However, users will be informed about the higher priority of the possible future request and, when this is issued, they will be asked to leave the on-demand room. The rule is valid unless the apartment that issued the usual request has reached its usage quota for the day/week/month/etc.

Proactive customization As we said, the room adapts its atmosphere so as to resemble the apartment that uses it, giving occupants the impression that they did not leave their dwelling at all.

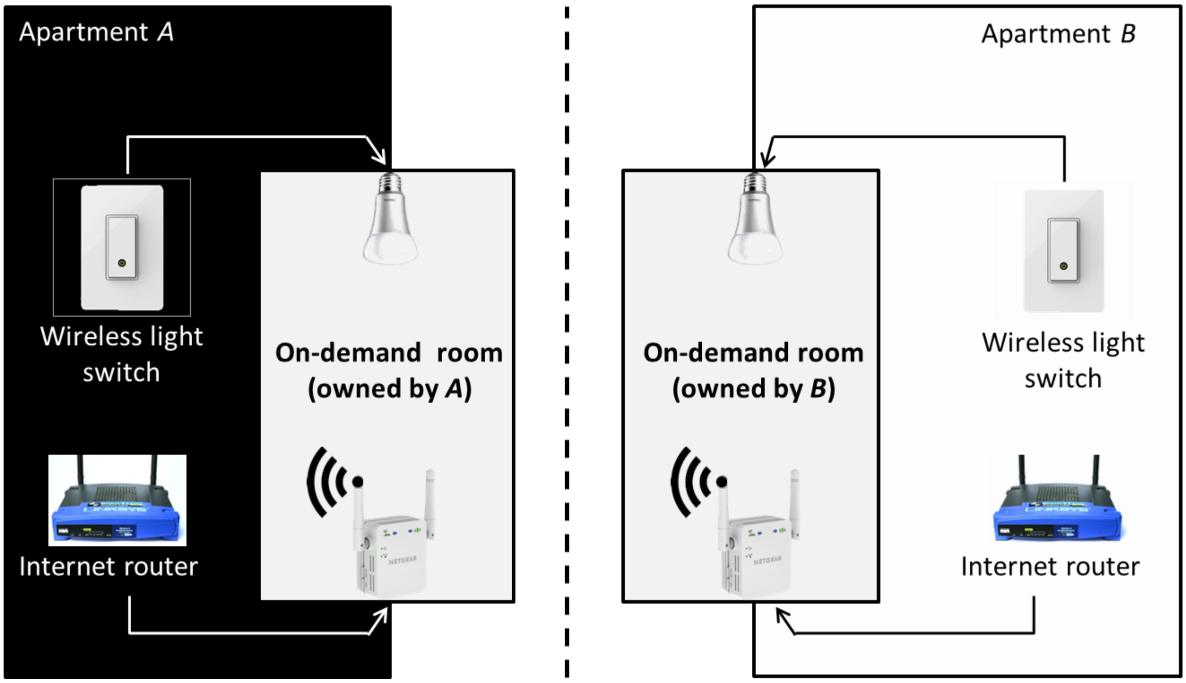

Figure 3: The room's equipment must be dynamically connected to the apartment that temporarily owns it

Some of the customizations require sizeable anticipation to produce remarkable effects by when the request is actually issued, like when managing heating, ventilation and air conditioning (HVAC). Giving the order when the room is requested would cause the occupant to wait a certain time before the preferred conditions are reached.

For this reason, some actions are realized proactively, by anticipating regular requests. For instance, heating is turned on early enough for the room to reach the preferred temperature of the user, before the request is actually issued.

3 Scientific goals and challenges

This section illustrates the scientific goals to pursue in order to make the on-demand room a reality. As we explained previously, when an apartment needs to be extended, a number of transformations are required to make the floating space *belong* to that apartment. The first goal is thus to dynamically reconfigure the devices and networks of the room, in order to connect them with the apartment that now owns them and to adapt their behavior to the respective preferences. This is described in § 3.1.

We also said that it is of prime importance that room usage conflicts are solved before they occur and that some actions are performed proactively, in order to make up for their delayed effect. The second goal to achieve is thus the prediction of future requests, obtained by discovering and learning user habits, as illustrated in § 3.2.

3.1 Goal 1 — Making the on-demand room *belong* to an apartment

Whenever an apartment is extended, a complex set of reconfigurations are required to make the on-demand room belong to the apartment and to give occupants the impression of owning the room. These were described in § 2.1 and raise the following research questions:

- How to dynamically provide an apartment with exclusive control over the room's equipment and designate it as the receiver of sensor and metering data? This reconfiguration should be entirely transparent for the equipment and sensors, so that real-world deployments can be simplified by using off-the-shelf devices.

- Conversely, how to dynamically reprogram the devices that have to substantially change their behavior after a reconfiguration? For instance, the network the Wi-Fi range extender is connected to has to change, as well as the devices allowed to control the room's blinds.

- Finally, how to make apartments' and room's equipment interoperate when they differ in technologies and/or vendors? This happens frequently in real deployments, where apartments and, possibly, the room have different owners, who make different choices in terms of brands and technologies. For instance, what if apartment A uses EnOcean wireless light switches [2], apartment B uses wired light switches and the room's light to control is a Wi-Fi light bulb?

These research problems will be addressed by using a modular architecture for the on-demand room and by dynamically reprogramming appliances, as explained in the two following subsections.

3.1.1 Abstracting physical devices

A partial solution to the aforementioned research problems is given by adopting a modular architecture: the on-demand room's equipment is not directly connected to any apartment. An abstraction module provides the decoupling between the room and the apartments. When the room gets a new owner, the devices and sensors are automatically connected to the new apartment.

Transparency With this approach, reconfigurations are completely transparent for the equipment of the on-demand room and of the apartments. For instance, the room's light continues to answer commands from the same virtual switch and the apartment's switch is still connected to the same virtual light: both the virtual elements are provided by the abstraction module. When and only when the apartment owns the room, switching actions will produce an actual effect on the room's light, as illustrated in Fig. 4.

Interoperability The proposed approach also allows devices to communicate with controllers of different technologies and brands, as the abstraction module can act as a bridge between heterogeneous communication media and protocols.

The general on-demand room modular architecture is illustrated in Fig. 5. As it can be seen, some devices are directly connected to the internal network of the apartment, without going through the abstraction module. It is the case of the network music player in the figure, which communicates with the music streaming server located in the owning apartment (and only in that apartment) thanks to the Wi-Fi range extender. In this case, interoperability between the music player and the streaming server relies on industrial standards like DLNA [1].

3.1.2 Dynamically reprogramming complex devices

We just described how to seamlessly plug the room in any apartment, without modifying the equipment's behavior. However, changing the on-demand room's owner can sometimes require reconfigurations that are not transparent for the devices. For instance, the ambient temperature set point of a thermostat should be dynamically changed to reflect the preferences of the new room's owner.

Reprogramming through commands In simple cases, devices can be reprogrammed by sending commands to them. For instance, this is true for most recent off-the-shelf thermostats, provided that the required wired or wireless communication infrastructure is available and that a common communication protocol is used by the thermostat and the controlling unit. When these assumptions hold, the change of room's owner will simply be dealt with by sending appropriate reconfiguration instructions to the devices.

Generally speaking, however, there are a number of settings that each user might customize the devices with. For instance, two different users might prefer different brightness and contrast levels for a TV screen, different songs to be reproduced by a music player, different pictures to be shown by a digital photo frame, different channel numbering for a TV set (since different households might have different subscriptions). These changes cannot be realized via simple commands to be sent to devices, so we need to consider a more general way to reprogram them.

Reprogramming in the general case Ideally, each household should feel like they have their own devices, that they can configure and customize. Settings should be stored and retrieved whenever that apartment owns the room, while being replaced when another household uses the room and its devices. This functionality is called *multi-user support* and some devices provide it natively, like personal computers and few mobile device types and vendors. The challenge is thus to extend the multi-user support to other devices of the consumer electronics industry.

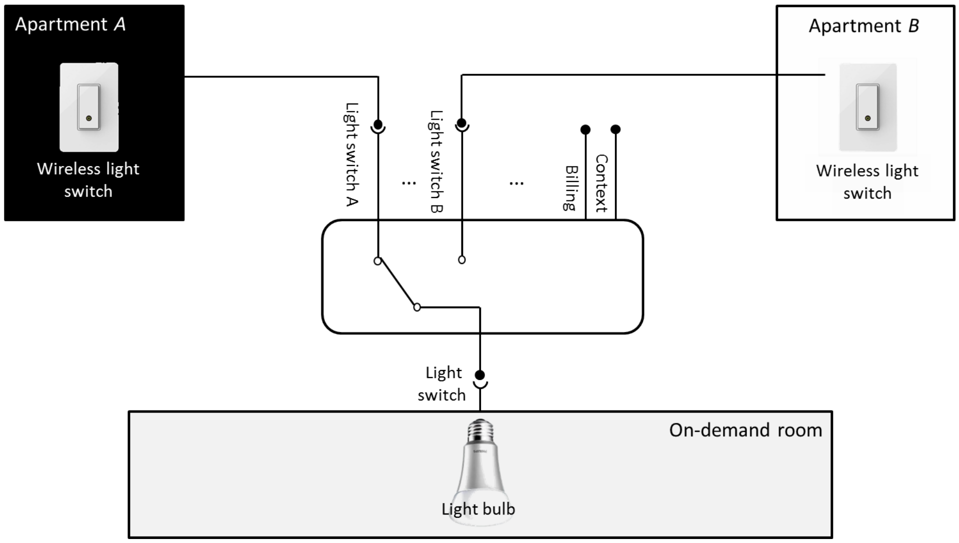

Figure 4: Abstraction of physical devices: only the light switch of the current room's owner will work

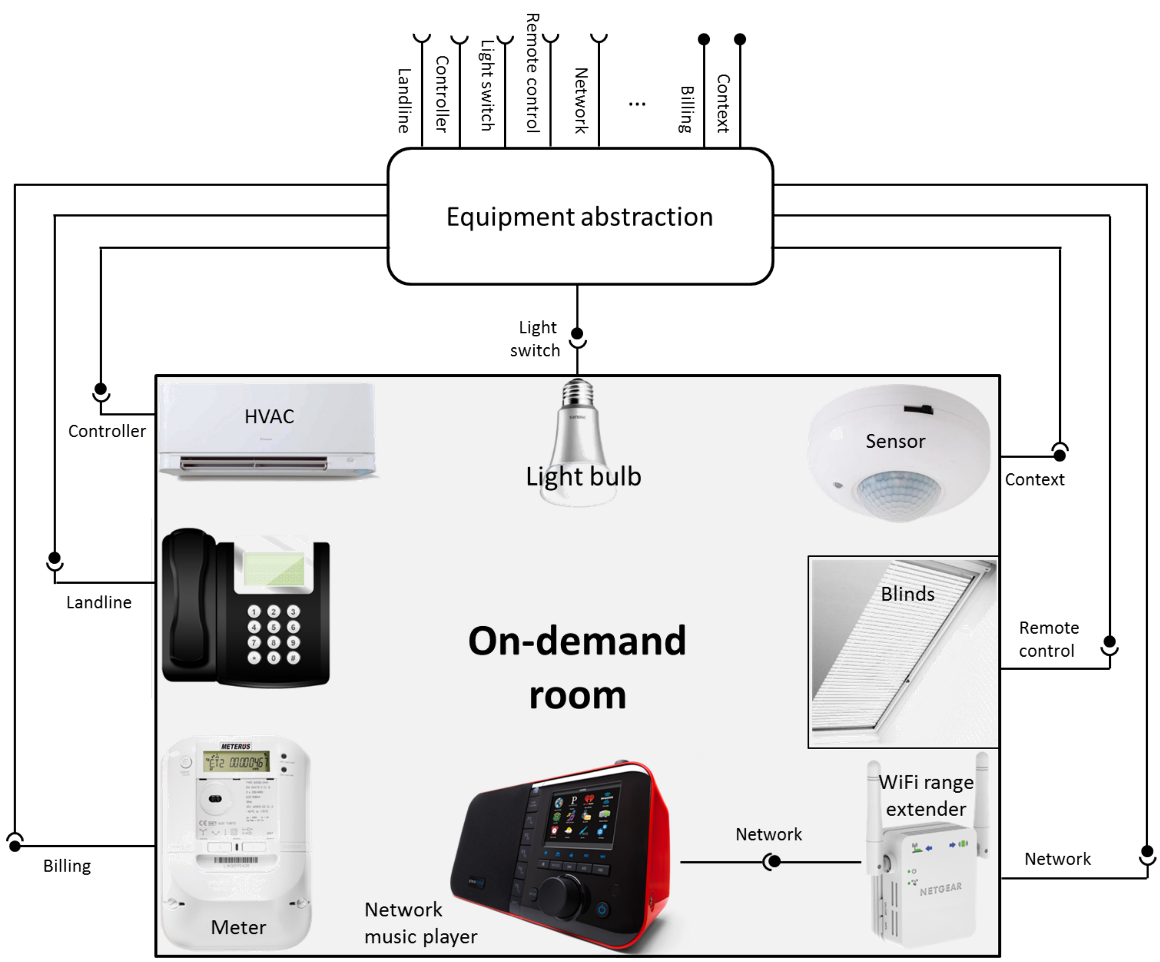

Figure 5: Modular architecture for the on-demand room equipment

To do this, it must be possible to have several "images" of the same device, to be chosen and executed depending on which apartment owns the room. This is similar to what is done in computer science with virtualization: different virtual machine images (called *virtual appliances*) can be saved and loaded on the same physical machine, allowing to quickly switch from a configuration to another. In our case, the images to be saved and loaded only include the custom data of the device (settings, files, history, etc.) and not the firmware (the software realizing the core functionalities) of the appliance.

3.2 Goal 2 — Automatically building a model of user behavior

The proactive functionalities of the on-demand room are the actions that it performs to anticipate future events, including proactive customization and resolution of conflicts (cf. § 2.2). They rely on the ability of the room to learn habits and preferences about its use. The problem consists in observing the behavior of users and discovering correlations among events; whenever these recurring patterns are learned, the room can predict future requests.

This problem can be solved using machine learning techniques. We now briefly present these techniques (cf. § 3.2.1) and choose which ones we need to realize the on-demand room solution (cf. § 3.2.2). Then, we will describe the challenges to face in order to achieve our goal of automatically building a model of user behavior (cf. § 3.2.3).

3.2.1 Existing machine learning approaches

Existing approaches can be divided in two categories: *supervised* and *unsupervised* machine learning techniques.

In *unsupervised* approaches, regularities and interconnections among events are discovered automatically and learned. To this end, several algorithms can be used; two examples are the topic model and the probabilistic context-free grammars [19]. In the topic model approach, the observed traces of simple activities are treated as a text document, where an activity is a word. Several topics are then discovered as recurring patterns of words. In the probabilistic context-free grammars approach, basic activities are characters of a grammar alphabet; rules, i.e., repeated sequences and complex combinations of activities, are automatically extracted from the execution traces.

Supervised approaches learn to automatically classify situations leveraging annotated training data, that is, traces of observed events coming with *labels* indicating what activity or habit each trace refers to. Supervised approaches include dynamic Bayesian networks, conditional random fields, hidden Markov models, artificial neural networks, support vector machines, k-nearest neighbors, etc. Many of them have been applied to human activity recognition [19].

3.2.2 Which approach?

In our case, the goal is not finding correlations among *any possible event*, but rather discover the conditions under which the room is used. In this sense, the fact that an apartment requested the room constitutes the *label* for the previous events, because it states that the previous actions and context are correlated with the request. For this reason, supervised machine learning techniques are the most suitable approach to solve our problem.

We will use supervised machine learning techniques to automatically build a model of user preferences and habits. When considering the on-demand room, these concern occupation habits and respective duration and privacy level, selected HVAC settings, room layout and other custom settings.

3.2.3 Challenges

To use supervised machine learning techniques in our case, it is very important to select the factors or *features* that contribute to the identification of user preferences and habits, so that the system considers them when learning.

The simplest solution would be considering the features as observable user actions and interactions with appliances, like returning home or moving from room to room. However, we cannot discover correlations only based on user actions. The reason is that these are not sufficient to reliably describe the behavior of occupants, as this depends on many contextual factors and there is not always a direct correlation between actions themselves.

For instance, the system may observe that the resident of apartment A frequently uses the on-demand room just after returning home. This would lead to associating the action of returning home to the action of requesting the on-demand room. However, it also happens that the person does not use the room after coming home and none of the actions performed previously helps distinguishing among the two situations. In this case, action patterns alone do not allow to reliably predict future events.

To address this problem, features should include other aspects of the situation, apart from user actions and interactions. There could be other conditions suggesting that the room is going to be requested. For instance, among many important factors that should be considered during the learning phase, we can cite:

- Temporal aspects: time of the day or day of the week in which the use of the room occurs, day of the year (e.g., National or religious holiday), period of the year (e.g., summer holidays, start of the new school year), etc.;
- Social aspects: presence of certain or all household members and their age.

So, instead of only learning and recognizing user action patterns, the system should also *consider the context associated with the actions*. If system designers provide the relevant features to machine learning algorithms, these are able to automatically discover regularities.

The challenge is thus to identify relevant and observable factors by analyzing domestic activity and existing examples of shared spaces use (e.g., shared rooms in apartment buildings). This requires an interdisciplinary effort, involving sociologists, psychologists and ergonomists.

4 Fostering socialization and solving usage conflicts

This section provides two additional categories of specifications of the on-demand room. The first group of specifications, illustrated in § 4.1, addresses the issues arising when multiple apartments request additional space at the same time. The second category of specifications, provided in § 4.2, describes how the on-demand room can be shared between adjacent apartments or even by all the building occupants, so as to foster socialization among building residents and to provide additional flexibility to the on-demand room. This section concludes with a formal specification of the case study as a state machine (cf. § 4.3).

4.1 Handling multiple requests

We describe here the working principles of the on-demand room when it comes to managing requests coming from multiple apartments. The presentation is organized in several paragraphs, each illustrating a particular aspect of the operation.

Assignments are inviolable Once the room has been assigned to an apartment x, it will remain so until x releases it. However, there are two cases in which x is misallocated the room. This happens whenever an apartment y requests it and: *(i)* the room had been booked by y (explicitly or as a result of automatic learning of habits, as explained in § 2.2) before it was assigned to x or *(ii)* apartment x has reached its usage quota (see below). In both cases, x is notified about the maximum duration of the occupation at the moment of requesting the room.

Conflict resolution When an apartment is misallocated the room for the reasons presented above, a notification will inform occupants that they should quickly leave the on-demand room. In case they refuse to do so, a conflict-resolution procedure, possibly involving a human supervisor (e.g., the building caretaker), will be started.

Economic model The additional space is pay-per-use, in order to prevent abuses like permanent occupation of the on-demand room by an apartment. When the floating space is not needed by the adjacent apartments, it may be assigned to any other building resident, so as to maximize its occupation.

Usage quota There is a limit on the amount of time during which an apartment can use the room. Different usage quotas can be set: maximum continuous use, maximum cumulative use per week/month/year, etc. Usage quotas apply to adjacent apartments and to other building occupants. For the latter users, the quota is calculated as a common cumulative usage time for all residents.

Minimum vacancy Even if an apartment has reached its maximum use per day/week/month, it will be granted access to the room, so as to best exploit the available built surface and maximize revenues (the room is pay-per-use). However, the room will have to be vacated as soon as a request is issued by an apartment that has not reached its quota.

Hygiene and cleanness Hygiene is favored by increasing the ventilation between successive occupancies. Cleanness can be ensured using robotic vacuum cleaners or scheduling human intervention.

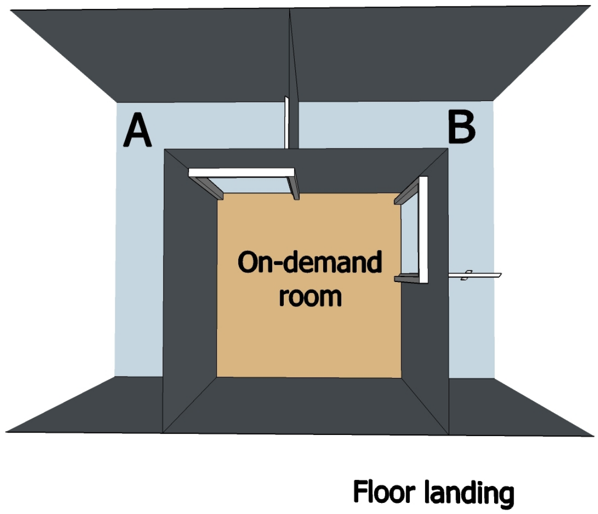

Figure 6: On-demand room shared between apartments A and B (intimate mode)

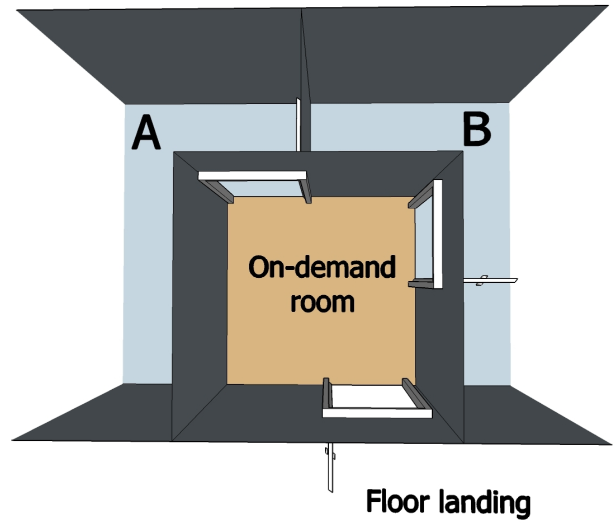

Figure 7: On-demand room shared between all building occupants (public mode)

4.2 Concurrent use of the on-demand room

We specify here some additional functionalities of the on-demand room, which allow to promote socialization among building residents and to mutualize the space to an even higher degree. The underlying idea is that the on-demand room can be used at the same time by several occupants.

The following paragraphs illustrate the material means for sharing the on-demand room and the rules that guarantee a fair use of it.

Privacy levels The floating space can be used as a common room between adjacent apartments or even be shared by all the building occupants. The possible privacy levels are, from the least to the most stringent one: *public* (shared with all authorized residents), *intimate* (shared between the two adjacent apartments A and B) and *private* (just one apartment). External residents (occupants of any apartment except A and B) can only ask for public privacy level.

Material means of sharing the room When a request is issued with intimate privacy level, two doors appear and allow to access the room from apartments A and B, as illustrated in Fig. 6. In public mode, an additional door connects the on-demand room with the floor landing and thus with the rest of the building (cf. Fig. 7). To prevent people from being locked in the room or out of their dwelling, all doors can become accessible from inside the room to their respective residents, thanks to an identity check mechanism (e.g., fingerprint check).

Satisfying privacy level requests The privacy level of any accepted request has to be satisfied. Therefore, if the room is currently occupied with a certain privacy level, say intimate, no additional requests with a different level (i.e., private or public) can be accepted.

Negotiations The occupants of the room can express their will to be notified when additional requests are issued during their stay. In that case, a digitally mediated negotiation with other residents could possibly result in reallocating the room or changing the privacy level during use. Occupants can release the room voluntarily or in exchange of other benefits (e.g., financial).

4.3 Formal specification of the on-demand room

We provided a detailed description of the on-demand room solution. This section presents a model of computation that formally specifies these working principles.

We first formalize the on-demand room as a finite state machine. Then, we highlight the limitations of this model of computation and propose a more suitable representation as a UML state machine.

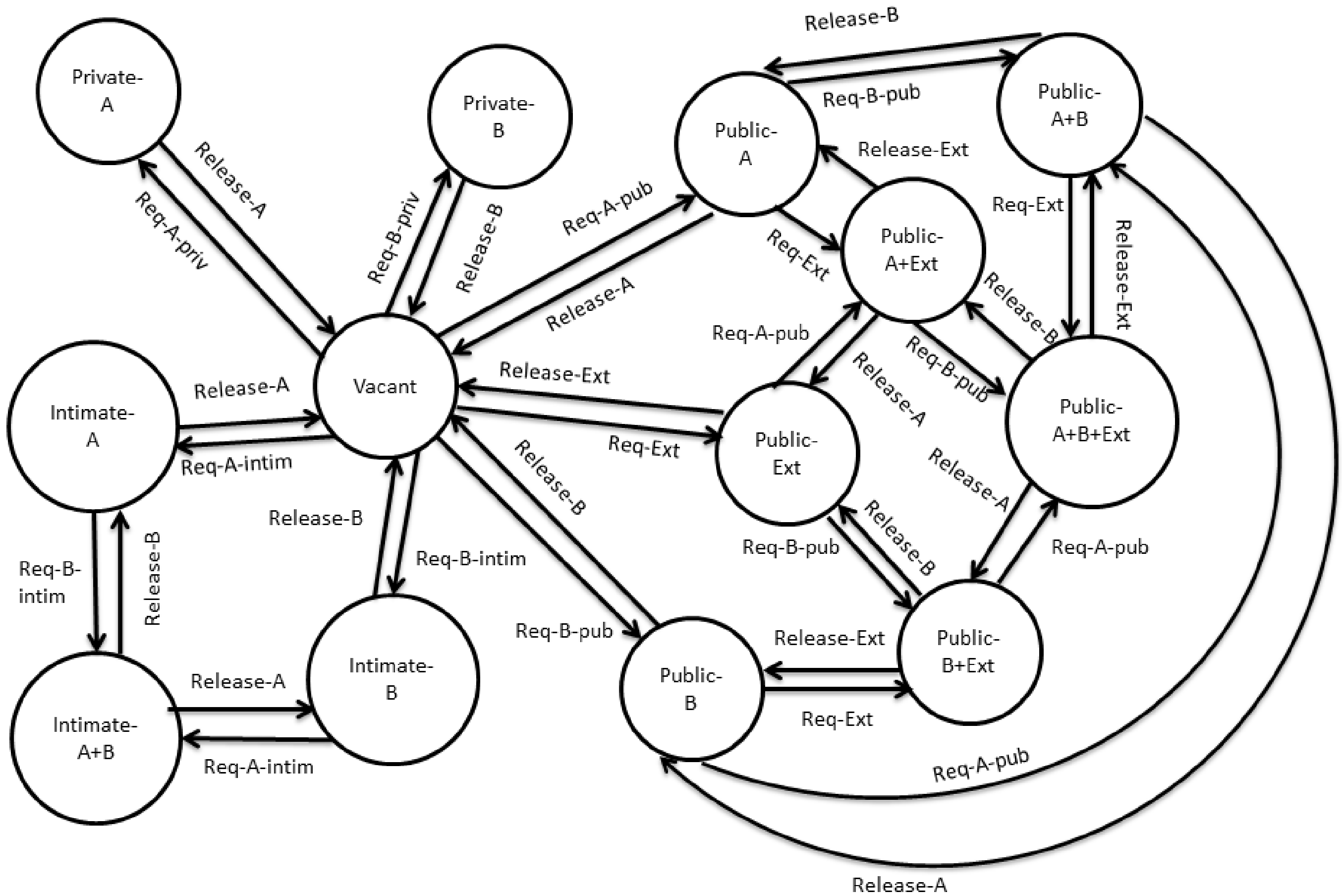

Figure 8: A subset of the functionalities of the on-demand room as a finite-state machine

The on-demand room as a finite state machine To formally specify the on-demand room working principles, we might use a finite state machine. It is a "model of computation consisting of a set of states, a start state, an input alphabet, and a transition function that maps input symbols and current states to a next state" [20].

Figure 8 shows a finite state machine, representing a subset of the functionalities of the on-demand room. Operations like keeping track of the number of external requests or dealing with excess of usage quotas are omitted, because the complexity of the model would dramatically increase.

The on-demand room as a UML state machine A UML state machine [13] is an alternative formalization that allows to overcome the drawbacks illustrated above. Figure 9 presents a UML state machine describing the on-demand room behavior. Since the UML specifications leave freedom to choose one's own syntax for operations and events [13], we followed the statechart description language coming with YAKINDU Statechart Tools 2 [15] plugin for Eclipse.

A UML state machine representation is much more expressive than a finite-state machine. Using this formulation, we can specify the operations associated with entering and exiting states (e.g., enabling or disabling doors), as well as with transitions (e.g., starting occupation timer, notifying occupants).

This formulation is also more compact, because *extended state variables* can model information like the number of occupants that issued a public request, which allows to know when the room has been released by all of them (cf. Fig. 9). The UML state machine allows us to model the full on-demand room behavior with just 8 states, while the finite state machine required 13 states to only partially model it.

Representing certain functionalities is very difficult with a finite-state machine but is simply done by a UML state machine, like managing requests when the current owner of the room has reached its maximum usage quota. We can see in the right-hand side of Fig. 9 that this is handled via a *choice* node: some transitions are possible only if the time is out

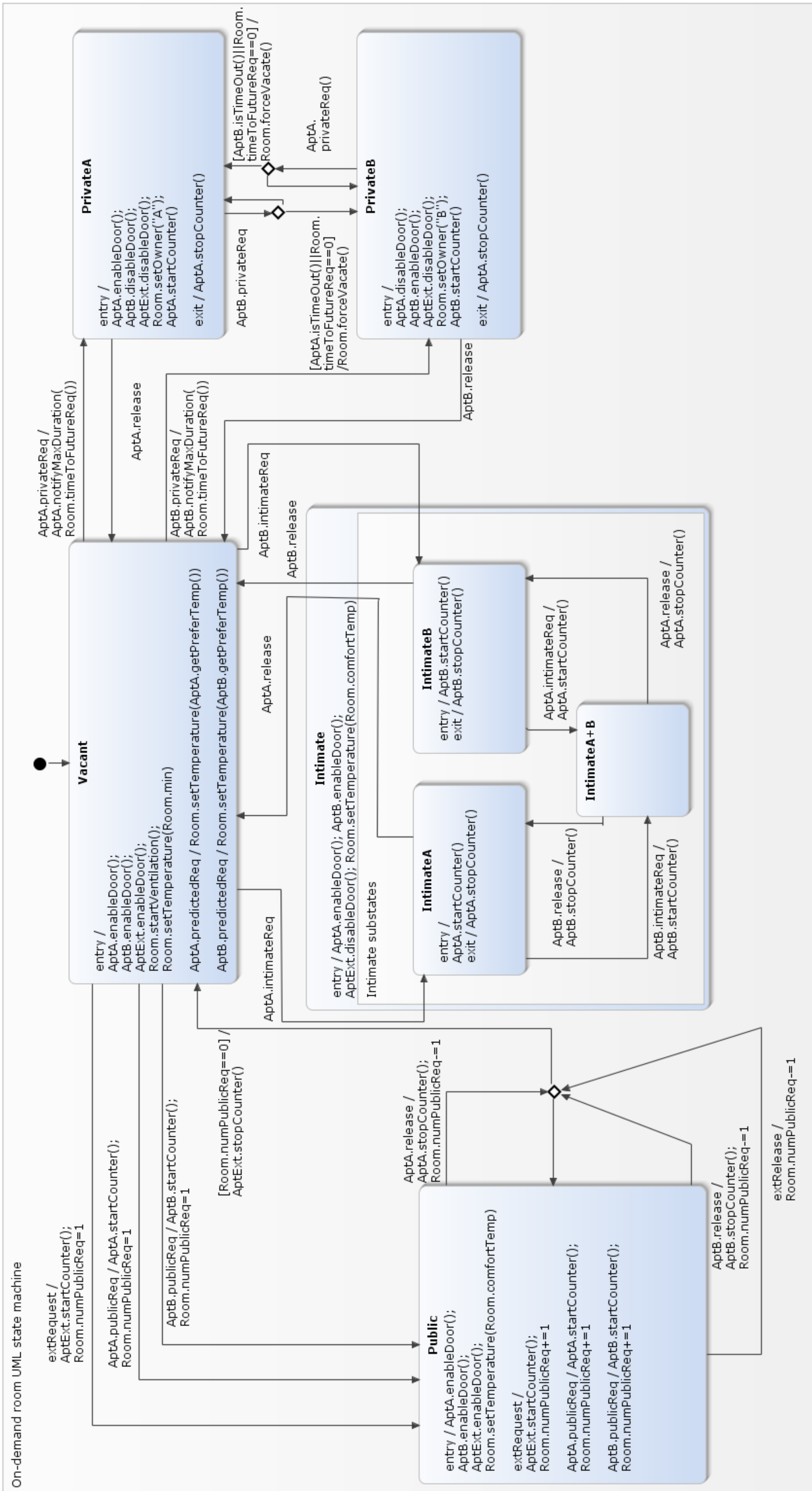

Figure 9: A UML state machine representing the on-demand room operation

for the apartment currenly owning the room. Similar choice nodes are required to connect private with public, private with intimate and intimate with public states, but they are omitted to ease the reading of the figure.

5 Implementation and evaluation

The on-demand room case study will be realized as an interactive application in an immersive virtual reality platform. Stakeholders and potential users will be able to see and interact with the on-demand room, leveraging the virtual environment.

This section presents the iterative methodology for the design and realization of the immersive application (cf. § 5.1), as well as the challenges for its realization (cf. § 5.2) and evaluation (cf. § 5.3).

5.1 Overall methodology

The implementation of the virtual environment will be realized in collaboration with architects and designers, so as to produce a technically sound and realistic prototype of the on-demand room. The process will be iterative and each iteration will be characterized by the following phases:

- requirement collection and analysis;
- design of a solution fulfilling the requirements;
- implementation of the solution as an immersive virtual environment;
- evaluation by stakeholders (including end users, companies and public authorities), psychologists, sociologists, etc.

At each step, the evaluation phase will produce the requirements for the next iteration (cf. § 5.3).

5.2 Realization challenges

In the realization of the immersive environment, there are several goals to be achieved through transdisciplinary collaboration. They are illustrated below.

5.2.1 Architectural modeling

We will need to model a realistic architectural setting, including the layout and appearance of the on-demand room and its neighboring apartments. We will benefit from the help of architects and designers.

We will use 3D architectural modeling software supporting the BIM (Building Information Modeling) standard data sharing format [5]. This format allows to reuse the same model in different, industry-specific software and to realize various engineering processes in parallel. This allows to save time, to avoid errors and to keep a unique, updated representation of the building.

5.2.2 Realizing the virtual environment and the application logic

For our demonstration, we will rely on Immersia [12], a large virtual-reality platform dedicated to real-time, multimodal (vision, sound, haptic, BCI) and immersive interaction. In Immersia, images are rendered on four glass screens, located on the front, on the sides and on the ground, as illustrated in Fig. 10. The platform is 9.6 m wide, 2.9 m deep and 3.1 m high. A tracking system, composed of 16 infrared cameras, enables real objects and people to be tracked within the scene. Images are recomputed as the user moves to fit his point of view, together with high-resolution rendering, active stereoscopy and homogeneous coloring, thereby delivering a visually realistic experience.

The architectural model of the on-demand room will be imported in Unity [14], a game development software that, used in combination with MiddleVR [8], allows to deploy, visualize and interact with the model inside Immersia. The working logic of the room, described the previous sections and formalized in § 4.3, will be implemented using Unity scripting facilities.

5.2.3 Realizing a hybrid real/virtual environment

In order to make the immersive experience more realistic, we will integrate in the application few real devices and sensors, realizing a hybrid (also known as *mixed reality*) application. The real devices might include light bulbs, Wi-Fi range extenders and various sensors.

These devices will be controlled by the application, just like virtual ones, and sensors will provide real data about users. For instance, a virtual switch might turn on a real light bulb (or vice versa) and real wearable sensors and handheld devices will allow users to interact with objects and devices in the virtual environment.

5.2.4 Designing suitable interaction modalities

Suitable interaction modalities and interfaces will have to be designed. First of all, interfaces are required to provide occupants with relevant information concerning their use of the room (e.g., cumulative occupation time and financial cost) and its schedule, to be shared with other apartments' occupants.

Appropriate interaction modalities will also be introduced, so that residents can collaboratively define the schedule of the on-demand room and solve usage conflicts.

5.3 Evaluation challenges

The prototype of on-demand room will be evaluated under different points of view, including user experience, technical soundness and resource efficiency, as illustrated below.

User experience evaluation We will assess how people appropriate the on-demand room and whether the system answers inhabitants' needs. The appropriation evaluation will establish if users build up their own knowledge of system capabilities and elaborate their own experience leading (or not) to an invisible use.

The immersive virtual environment will allow situating users in realistic conditions of use. Their behavior will be recorded, analyzed and used in interviews involving self-confrontation. This will allow reconstructing their concerns in situation and harvesting their individual and collective points of view (i.e., cognitive, emotional, subjective, etc.).

Decision-making and learning algorithms evaluation We will evaluate how well the interactive application performs with respect to the on-demand room specifications, provided in § 4.3. We will test the system and verify whether it has the expected behavior. Access to the room will have to be granted to apartments having requested it, with the appropriate privacy level and consistently with the state of the room, resulting from its history of use. The reconfiguration and customization of the room will have to follow that decision.

Figure 10: The immersive virtual reality platform *Immersia*

Evaluating the ability of the system to learn user preferences and habits requires performing tests that last over time. This is difficult to realize in a virtual reality platform. To overcome this limitation, we will generate synthetic traces of execution, starting from realistic patterns of activity and room use. We will feed the application with the traces and verify whether the patterns are correctly discovered and learned. Based on that model, the system will have to correctly schedule and grant access to the room in a predictive fashion.

Evaluation of space and energy gain The objective of this evaluation phase is to quantify the overall benefits of the on-demand room in terms of space and energy efficiency, compared to a number of additional private rooms, belonging to apartments. Several evaluation indices will be used, including: occupation time per room, ratio of occupied surface over built surface, energy use, etc. The evaluation will be performed on realistic execution traces, compared using those indices, for an apartment building in different configurations: equipped with an additional room per apartment, with a simply shared room and with an on-demand room.

Overall considerations will be issued to verify whether the room allows to find a good trade-off between optimal use of resources and maximization of user comfort, which are often contradictory objectives.

6 Related Work

Related research activities have been named *kinetic*, *responsive* and *interactive* architecture [18], as well as *architectural robotics* [21]. Some of the major initiatives are illustrated below:

- The Places of Living and Work research theme at the City Science initiative at MIT Media Lab proposes projects of "personalized, transformable urban housing" and "time-shifted, shared space-on-demand for collaborative work" [9].
- The Living Architecture Lab at the GSAPP, Columbia University, "aims both to make visible the invisible forces that shape our world, and to explore the potential for architecture to transform in real time based on these forces" [7].
- The Genetic Architecture group at Universitat Internacional de Catalunya (UIC) "works on applying genetics to the field of architecture in an interdisciplinary way, from two perspectives: the real, natural, and direct, and also the metaphorical, artificial, and digital" [3].
- The Hyperbody group is the knowledge center for Nonstandard and Interactive Architecture at the TU Delft [4]. The laboratory works on the change in conception and realization of design due to digital design and production methods and engages the new modes of architectural practice that embrace the shift from standard to nonstandard structures and from static to dynamic buildings.
- The Laboratory for Integrative Design (LID) is a research group from the University of Calgary that brings together researchers from multiple disciplines [6]. Researchers at LID operate at the intersection between design, its allied disciplines of engineering and production, and other fields, such as computer science, material science, mathematics and biology.
- The Office for Robotic Architectural Media & The Bureau for Responsive Architecture (ORAMBRA) "develops new construction systems and components for buildings. Focusing upon rethinking construction alongside the emergence of responsive technologies, the office is recognized for developing structural shape change technologies that alter the way that buildings use energy" [10].
- The Bartlett Space Syntax Laboratory is the international center of the theory and methodology known as "space syntax" [11]. Its team of researchers studies the effects of spatial design on aspects of social, organizational and economic performance of buildings and urban areas, uniquely combining the creation of software for spatial analysis and design with observation of function. Its theoretical and methodological innovations intersect with a variety of disciplines, including anthropology, archaeology, geography, computer science, psychology, sociology, mathematical modelling, public health and physics.

7 Conclusions

This paper presented a case study of metamorphic housing called on-demand room. We described the goal of dynamically extending a dwelling, as well as the transformations in the material and digital world that make the additional space belong to it.

The paper also presented the strategies for proactively solving conflicts in the use of the limited floating space, which are based on learning user habits. Finally, we illustrated the important efforts required to define, implement and evaluate the case study in an immersive virtual reality platform.

7.1 Work plan

Our first steps to reach the goals presented in this paper will consist in introducing suitable strategies to dynamically reconfigure the behavior and connections between devices. A particularly promising approach to realize such transformations is represented by *models@run.time*: "runtime adaptation mechanisms that leverage software models" [17].

We will also immediately start the realization of the immersive virtual reality environment, using the software Unity3D and its plug-in MiddleVR for the immersive capabilities [8]. This will allow to quickly obtain a demonstrator of the case study and to iteratively improve its specifications.

Considerations concerning the real-world deployment of metamorphic housing will be taken into account. Namely, all the algorithms will be designed so as to work without relying on an external infrastructure, in order to preserve residents' privacy. Furthermore, we will assume that a part of the physical reconfigurations will be performed by humans instead of mechanical effectors. For instance, the on demand room might be cleaned by a person in between uses and people might manually reconfigure a part of the room's furniture to fit their preferences.

7.2 Perspectives

The models and algorithms to be introduced through this research are generic and will be applicable to other examples of metamorphic housing. We provide below a non-exhaustive list of potential future case studies, which would benefit from the outcomes of this research.

- **Splitting the floating space into separate smaller rooms**, thanks to mobile partitions and control algorithms. This would allow to extend apartments in spite of possibly time-overlapping requests. The models and algorithms used in the on-demand room for allocation of the space and for the dynamic transformations could be reused.

- **Dynamically changing the room's internal layout and aspect** so as to reflect user preferences, also with respect to declared or expected activity to be performed in the room (e.g., arrangement and type of furniture). The dynamic change of ownership of devices proposed by the on-demand room use case is applicable in this example. Indeed, when a room is entirely reconfigured to change from a kitchen to a bedroom, a number of changes in the operation and interconnection of devices must be realized.

- **Defining an extension of the Building Information Modelling (BIM)** data sharing format [5], leveraging the experience of this case study. The extension would consist in a formal language that allows to specify the dynamic behavior of the building and of the architectural structures.

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